

Timing Noise in Pulsars and Magnetars and the Magnetospheric Moment of Inertia

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We examine timing noise in both magnetars and regular pulsars, and find that there exists a component of the timing noise (σ_{TN}) with strong magnetic field dependence ($\sigma_{\text{TN}} \sim B_o^2 \Omega T^{3/2}$) above $B_o \sim 10^{12.5} \text{G}$. The dependence of the timing noise floor on the magnetic field is also reflected in the smallest observable glitch size. We find that magnetospheric torque variation cannot explain this component of timing noise. We calculate the moment of inertia of the magnetic field outside of a neutron star and show that this timing noise component may be due to variation of this moment of inertia, and could be evidence of rapid global magnetospheric variability.

Introduction.— The spin evolution of pulsars and magnetars is studied by long term monitoring of pulse arrival times, allowing the spin period, spin-down rate, orbital motion and astrometric variations of the neutron star to be inferred. The variation of these pulse arrival times from the best fit models of the timing evolution is referred to as timing noise.

Timing noise was first observed in the Crab pulsar [1] and has been identified as a ubiquitous property of pulsars [2]. Recently much effort has been made to understand the stochastic timing noise in millisecond pulsars, as timing arrays of low-noise recycled pulsars will allow the detection of nanohertz gravitational waves [3]. Millisecond pulsars typically have relatively low inferred surface magnetic field ($B_o \sim 10^7 - 10^8 \text{G}$), due to age and accretion history.

Most isolated pulsars have spin-down inferred surface magnetic fields in the range $B_o \sim 10^{11} - 10^{13} \text{G}$, while the highest known magnetic fields are possessed by magnetars ($B_o \sim 10^{13} - 10^{15} \text{G}$). Magnetars include Anomalous X-ray Pulsars (AXPs) whose X-ray luminosities dwarf their spin down luminosities and most likely originate from internal magnetic field decay [4]; and Soft Gamma Repeaters (SGRs), hard X-ray transient sources that can undergo extreme outbursts.

Mode-changing and nulling behaviors in pulsars have been linked to spin-down torque variations [5, 6], implying that such behavior is indicative of variations of the open field line regions of the magnetosphere. Recent simultaneous X-ray and radio observations of PSR B0943+10 [7] have challenged existing pulsar emission theories and provided evidence that such variability is indicative of rapid *global* variations of the magnetosphere.

In this Letter we study the timing noise for radio pulsars and magnetars, inferring a source of timing noise in high B-field pulsars and AXPs which correlates strongly with magnetic field. We examine physical models to explain the dependence of this timing noise on the spin-down inferred magnetic field, and identify this timing noise as evidence for global magnetospheric variability.

Timing Noise Analysis.— Long term pulsar timing irregularities have enjoyed a long history of detailed analysis [see e.g. 8–12]. Here we adopt the approach of modelling timing noise as a random walk process [1, 13, 14]. In particular, we utilize the formalism of Cordes [14] in order to define the random walk strengths of various processes: $S_{\text{PN}} = R \langle (\delta\phi)^2 \rangle$,

for a random walk in phase; $S_{\text{FN}} = R \langle (\delta\Omega)^2 \rangle$, for a random walk in frequency; and $S_{\text{SN}} = R \langle (\delta\dot{\Omega})^2 \rangle$, for a random walk in spin-down rate, where R is the occurrence rate of the random walk steps, and $\langle \cdot \rangle$ indicates an ensemble average. The quantities $\delta\phi$, $\delta\Omega$, and $\delta\dot{\Omega}$ denote stochastic variations in phase, frequency, and spin-down rate, respectively.

These strengths can be estimated from timing parameters of a given pulsar and represent the strength of the assumed random walk

$$S_{\text{PN}} \approx 2C_{0,m}^2 \sigma_{\text{TN}}^2 T^{-1}, \quad (1)$$

$$S_{\text{FN}} \approx 12C_{1,m}^2 \sigma_{\text{TN}}^2 T^{-3}, \quad (2)$$

$$S_{\text{SN}} \approx 120C_{2,m}^2 \sigma_{\text{TN}}^2 T^{-5}, \quad (3)$$

where, T is the time span over which the observations were (uniformly) taken, σ_{TN} is the rms phase residual of the data for a given timing solution, and $C_{0,m}$, $C_{1,m}$ and $C_{2,m}$ are correction factors [14, 15] to compensate for the power of the random walk that has been removed by the m th order polynomial fit that occurs when the residuals are determined.

Previous analyses [8, 10, 12] have shown that simple random walk processes cannot explain the totality of timing noise, with the different strengths sometimes varying strongly even for the same pulsar as a function of timespan T . We argue that if some random walk timing noise component becomes dominant as the magnetic field increases 8 orders of magnitude from $\sim 10^7 \text{G}$ to $\sim 10^{15} \text{G}$ this should result in a lower bound in the distribution of the random walk strength that scales with the magnetic field.

In Figure 1 we show the random walk strengths for various pulsars versus the spin-down inferred surface dipole magnetic field strength. The strength of the frequency noise and spin-down noise has been normalized by Ω^2 and $\dot{\Omega}^2$, respectively, so that the strengths can be compared across pulsars with differing timing profiles. Here, we utilize published timing data from Jodrell Bank Observatory [8], and the Parkes 64m radio telescope [16–21]. We also include the X-ray timing results from the well-timed AXPs: 1E 1841–045 [22], RXS J170849.0–400910 [22], 4U 0142+61 [23], and 1E 2259.1+586 [24]. We do not include the timing for AXP 1E 1547.0–5408 [25], as the timing observations have only been taken post-outburst, nor AXP 1E 1048.1–5937 [26], as the timing solution presented in the literature was fit using fifth order splines rather than a simple polynomial fit, due to instabil-

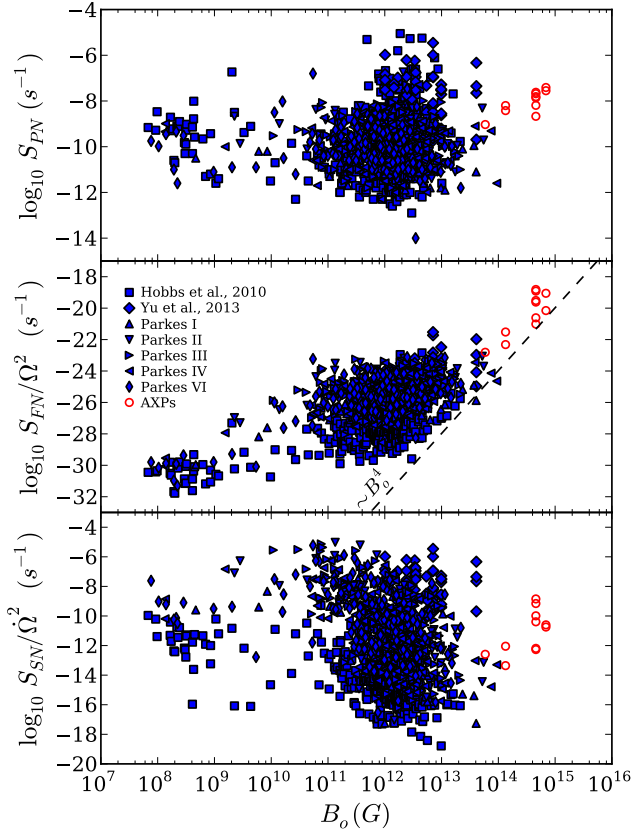


FIG. 1. Effective random walk strength for various pulsars as a function of spin-down inferred magnetic field strength (B_o). The frequency noise (FN) and spin-down noise (SN) strengths have been normalized by Ω^2 and $\dot{\Omega}^2$, respectively, to be comparable between systems. The blue points denote normal pulsars, with radio timing information taken from Hobbs *et al.* [8], Yu *et al.* [16], and the Parkes multi-beam survey [17–21]. The red circles label AXP timing epochs, with X-ray timing information taken from Dib *et al.* [22, 23], and Gavril and Kaspi [24]. The effective strength of the frequency noise random walk shows a strong trend with magnetic field strength. In particular the lower bound of the frequency noise strength distribution appears to rise sharply for $B_o \gtrsim 10^{12.5}$ G as $(S_{\text{FN}}/\Omega^2)_{\text{min}} \sim B_o^4$, such that $(\sigma_{\text{TN}})_{\text{min}} \sim B_o^2 \Omega$.

ity of the spin-down of 1E 1048.1–5937. We also ignore the timing properties of SGRs (unlike Shannon and Cordes [9]), which are only timed in a phase connected fashion for short periods following outbursts where timing noise would likely be elevated by the burst activity. In quiescence, where the timing noise would not be dominated by such events, SGRs are faint and have not been observed with sufficient regularity for a phase connected solution to emerge.

While there is no obvious correlation between magnetic field strength and the random walk strengths for phase noise (S_{PN}) or spin-down noise ($S_{\text{SN}}/\dot{\Omega}^2$) in Figure 1, there appears to be a weak correlation of the FN strength (S_{FN}/Ω^2) with B_o

across the range of magnetic field¹. We note, however, that above a field strength of $B_o \gtrsim 10^{12.5}$ G, the lower bound of the FN strength distribution rises sharply with $(S_{\text{FN}}/\Omega^2)_{\text{min}} \sim \Omega^2/\Omega^6 \sim B_o^4$. We focus on FN as the change in S_{FN} along this lower envelope is larger than the intrinsic scatter of the distribution for FN (particularly due to the inclusion of AXP timing data). Thus, we infer that timing noise has a component which depends strongly on the magnetic field and becomes dominant as the magnetic field increases such that $(\sigma_{\text{TN}})_{\text{min}} \sim B_o^2 \Omega T^{3/2}$ above $B_o \gtrsim 10^{12.5}$ G. These scalings are within the 2σ confidence intervals for the timing noise scalings inferred by [9] for magnetars, except for the dependence on T , which may be different due to their inclusion of SGRs.

Caution must be used in interpreting such scalings as $B_o^2 \sim \dot{\Omega}/\Omega^3$, and is only inferred from the spin observables. With this in mind, we consider two different physical models of timing noise due to magnetospheric variability, torque variation, and moment of inertia variation.

Magnetospheric Torque Variation.— Spin-down torque variation and mode-changing are associated with perturbations of the open field lines [5, 6]. The effect of these torque variations on the timing noise has been explored in detail by Cheng [27], who showed that the frequency noise strength for torque variability should scale as $S_{\text{FN}}/\Omega^2 \sim \dot{\Omega}^2/\Omega^3 \sim B_o^4 \Omega^3$, which is inconsistent with the scaling discussed above. Thus, while this source of noise may dominate in some pulsars, particularly those where significant pulse-shape changes are observed, it is not the source of the high magnetic field timing noise floor evident in Figure 1.

Magnetospheric Moment of Inertia.— The angular momentum content of a small volume of the magnetosphere in the inertial frame [28] is $d\mathbf{L} = (\mathbf{r} \times \mathbf{S}/c^2)dV$ where \mathbf{S} is the Poynting vector and dV is the volume element. In a co-rotating ideal-MHD magnetosphere with angular velocity $\boldsymbol{\Omega}$, we can evaluate this as

$$d\mathbf{L} = \left[\mathbf{r} \times (\boldsymbol{\Omega} \times \mathbf{r}) \frac{B^2}{4\pi c^2} - (\mathbf{r} \times \mathbf{B}) \frac{\mathbf{B} \cdot (\boldsymbol{\Omega} \times \mathbf{r})}{4\pi c^2} \right] dV. \quad (4)$$

In cylindrical coordinates, (ϖ, z, ϕ) , the component of the angular momentum along the rotation axis is $dL_z = \frac{1}{4\pi c^2} \varpi^2 \Omega (B_\varpi^2 + B_z^2) dV$. Thus the angular momentum of the magnetosphere in the direction of the rotation is given by the integrated angular momentum of the magnetic energy density with the component of the magnetic field in the azimuthal direction removed, as the component of the magnetic field in the direction of motion should not contribute to the Poynting flux in that direction.

¹ The weak correlation of this timing noise with magnetic field for lower field strengths has been noted previously, see e.g. Figure 9 of Hobbs *et al.* [8], where timing noise is measured by the parameter $\sigma_z(10\text{yr})$. The onset of a sharp increase in $\sigma_z(10\text{yr})$ above $B_o \sim 10^{12.5}$ G can also be seen in this figure, but is not mentioned by the authors. In Figure 1 the trend is more clear due to the inclusion of the AXPs.

For a dipole with magnetic moment μ_o , where $|\mu_o| = B_o r_{\text{NS}}^3$ and $2B_o$ is the field strength at the magnetic pole at the NS surface r_{NS} , we calculate the magnetospheric angular momentum (for light-cylinder radius $\varpi_{\text{LC}} = c/\Omega \gg r_{\text{NS}}$) using (4)

$$\mathbf{L}_B \simeq \frac{16}{15} \frac{\mu_o^2 \Omega}{c^2 r_{\text{NS}}} + \frac{1}{15 c^2 r_{\text{NS}}} (\mu_o^2 \Omega - [\mu_o \cdot \Omega] \mu_o). \quad (5)$$

For the aligned rotator this gives $\mathbf{L}_{B,\text{aligned}} \simeq (16/15) B_o^2 r_{\text{NS}}^5 \Omega / c^2$, while for the oblique rotator we have $\mathbf{L}_{B,\text{oblique}} \simeq (17/15) B_o^2 r_{\text{NS}}^5 \Omega / c^2$.

For a magnetic field strength $B_{15} \equiv B_o / 10^{15}$ G, neutron star radius $r_6 \equiv r_{\text{NS}} / (10^6 \text{ cm})$ and mass $M_{1.4} = M_{\text{NS}} / (1.4 M_\odot)$ we can compare the moment of inertia in the magnetosphere to that in the neutron star $I_B / I_{\text{NS}} = L_B / L_{\text{NS}}$,

$$\frac{I_{B,\text{aligned}}}{I_{\text{NS}}} \simeq 1.0 \times 10^{-6} B_{15}^2 r_6^3 M_{1.4}^{-1} \left(\frac{\eta}{2/5} \right)^{-1} \quad (6)$$

for the aligned rotator, where $\eta \equiv I_{\text{NS}} / (M_{\text{NS}} r_{\text{NS}}^2) = 2/5$ for a uniform rotating sphere. While this ratio depends strongly on the NS radius, typical equations of state which allow masses as large as the observed $2M_\odot$, have radii varying by at most $\sim 20\%$ over the range of expected NS masses [29, 30].

Magnetospheric plasma has at least the Goldreich-Julian density $\rho_{\text{GJ}} = \mathbf{\Omega} \cdot \mathbf{B} / [2\pi c (1 - (\varpi/\varpi_{\text{LC}})^2)]$ [31]. Near the NS surface, $\varpi \ll \varpi_{\text{LC}}$, the ratio of the Goldreich-Julian plasma energy density to the magnetic field energy density is $E_{\text{GJ}}/E_{\text{mag}} \sim 10^{-19} (\Omega/s^{-1}) (\mu_o/10^{30} \text{ G cm}^3)^{-1} (\varpi/10^6 \text{ cm})^3$. The radius ϖ_{eq} at which the energy density of the plasma is comparable with the magnetic field energy density can be estimated as $\varpi_{\text{eq}} = \varpi_{\text{LC}} \sqrt{1 - 4c^4 m_e / (\mu_o \Omega^2 e)}$. For a pulsar with $B_o \simeq 10^{12}$ G, this gives $\varpi_{\text{eq}} \simeq 0.999 \varpi_{\text{LC}}$ which is extremely close to the light cylinder. Relativistic force-free solutions of the magnetosphere that take into account the poloidal currents [32] lead to similar results as their differences are concentrated near the light cylinder, while most of the mass and energy density is near the NS surface. Thus the contribution of the Goldreich-Julian plasma to the moment of inertia of the magnetosphere can be safely ignored.

Magnetospheric Variability.— Mode-changing and nulling events are related to rapid variability of the open field line region of the magnetosphere [5, 6]. Recent observations have shown that such rapid variability may be a global magnetospheric phenomenon [7], and not simply confined to the open field line region. Thus, the magnetospheric moment of inertia could also vary on a short timescale.

The equation of motion for rotation is $\frac{d}{dt}[I(t)\Omega(t)] = N(t)$, where $N(t)$ is the external torque on the neutron star. We define $I = I_c + \delta I(t)$ where $\delta I(t)$ is a stochastic component to the moment of inertia that we will associate with magnetospheric variations, and I_c is the moment of inertia of the NS that is strongly coupled to the crust such that the coupling timescale is much shorter than the timescale of the variability. This strongly coupled component is the part of the star that can then respond effectively to the moment of inertia variation. We also define $\Omega(t) = \Omega_S(t) + \delta\Omega(t)$ where $\Omega_S(t)$ is the smooth

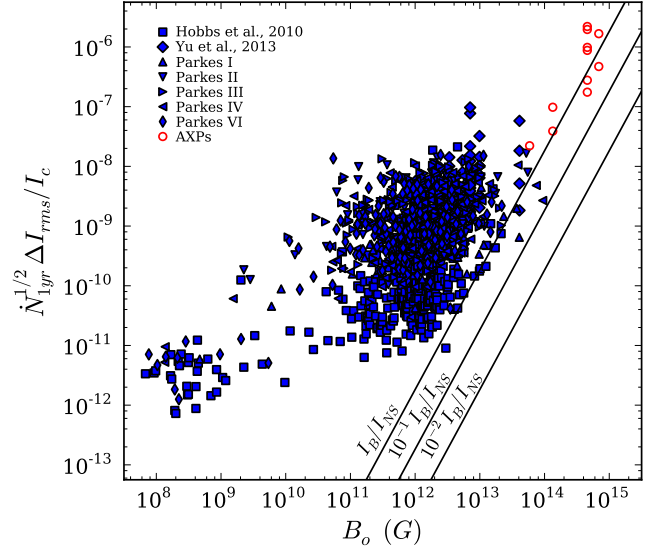


FIG. 2. A measure of the moment of inertia variability $\dot{N}_{1\text{yr}}^{1/2} \Delta I_{\text{rms}} / I_c$ versus the surface magnetic field strength B_o for the same pulsars and magnetars shown in Figure 1. $\dot{N}_{1\text{yr}}$ is the number of moment of inertia random walk steps that occur per year. We compare this to the fractional moment of inertia contained in the magnetosphere, I_B / I_{NS} (assuming an aligned dipole for a $1.4 M_\odot$ mass neutron star with radius 12 km).

polynomial behavior of the angular velocity and the stochastic component is $\delta\Omega(t)$. Ignoring spin-down torque variations that could occur from magnetospheric variation near the open field lines, we solve for the $\delta\Omega(t)$ to first order in $\delta I / I_c$ and $\delta\Omega / \Omega_S$, assuming that the torque takes the form $N = \alpha \Omega^n$ where n is the braking index of the neutron star. This gives

$$\delta\Omega(t) = -\Omega_S(t) \frac{\delta I(t)}{I_c} - \int_0^t n \dot{\Omega}_S(t') \frac{\delta I(t')}{I_c} dt' \quad (7)$$

The second term is much smaller than the first term as long as the observed time span is short compared to $T \ll \tau_c \equiv \Omega_S / 2\dot{\Omega}_S \gtrsim 10^4$ years for typical magnetars.

Modeling the stochastic variation of the moment of inertia as a random walk we have $\delta I(t) = \sum_j \Delta I_j H(t - t_j)$, where ΔI_j and t_j are random amplitudes and times, while $H(t)$ is the unit step function. The first term of equation (7) then corresponds to a random walk in frequency, while the second term is a random walk in frequency derivative. Considering realistic observing spans the first term must dominate. Using the definition of S_{FN} , the variability of the moment of inertia can then be expressed in terms of the frequency noise random walk strength,

$$\dot{N}_{1\text{yr}}^{1/2} \Delta I_{\text{rms}} / I_c = \sqrt{(S_{\text{FN}} / \Omega^2) \times 1 \text{ yr}}, \quad (8)$$

where we have chosen to use the parameter $\dot{N}_{1\text{yr}} \equiv R \times 1 \text{ yr}$, the number of random walk steps per year. This value is plotted against magnetic field strength in Figure 2, as well

as various fractions of the magnetospheric moment of inertia I_B/I_{NS} , assuming an aligned magnetic dipole and a neutron star mass $1.4M_\odot$ and radius 12 km. We note here that above $B_o \approx 10^{12.5} \text{ G}$ the moment of inertia variability is bounded by $\dot{N}_{\text{yr}}^{1/2} \Delta I_{\text{rms}}/I_c \sim (0.1-1)I_B/I_{NS}$. If the timing noise observed at this lower bound is due to variability of the moment of inertia it follows then that $\dot{N}_{\text{yr}}^{1/2} (\Delta I_{\text{rms}}/I_B)(I_{NS}/I_c) \sim 0.1-1$.

Assuming $\dot{N}_{\text{yr}} \sim 10^5 - 10^7$ to reflect the variability timescales observed in pulsar nulling or mode-changing [5], and the strongly coupled fraction of the NS moment of inertia to be $I_c/I_{NS} \sim 0.1$ [27] over the variability timescale, we can estimate the rms amplitude of the magnetospheric moment of inertia variability, $\Delta I_{\text{rms}} \sim (10^{-4} - 10^{-6}) I_B$.

The magnetosphere is expected to be dynamic near the light cylinder, due to reconnection and instability [32, 33]. This may also contribute to the timing noise through magnetospheric moment of inertia variation, however the amplitude of this contribution to the random walk strength is suppressed a factor $(r_{NS}\Omega/c)^2 \sim 10^{-9} \text{ s}^2 \Omega^2$, due to the much weaker contribution to the moment of inertia near the light cylinder. We find that this component is too small to contribute substantially to the timing noise discussed above. This implies that the variability of the moment of inertia must instead occur near the NS surface, where the magnetospheric moment of inertia is largest.

Comparison to Glitch Sizes.— Glitches in pulsars and magnetars are impulsive increases in the rotation frequency. They are thought to represent a sudden transfer of angular momentum from a more quickly rotating super-fluid component to the NS crust. While glitches can vary across several orders of magnitude in size for a single pulsar, the smallest detectable glitch sizes can also serve as a measure of timing noise.

The smallest detectable glitch size can be estimated from the timing noise level, by comparing the (pre-fit) phase change due to the stochastic noise over the data span required to infer the existence of small glitch, to the phase change due to the glitch itself, $\Delta\phi_{\text{TN}}(\Delta t) \approx S_{\text{FN}}^{1/2}(\Delta t)^{3/2}/\sqrt{12} \lesssim \Delta\Omega_{\text{glitch}}\Delta t$ for frequency noise. If the expected phase change due to the noise is larger than the phase change due to the glitch, then a glitch cannot be definitively identified. Oversimplifying the details of observational cadence and analysis we can then estimate the smallest observable glitch size by assuming that several (~ 3) time-of-arrival observations, with cadence ~ 1 month, on either side of a small glitch are needed to characterize it. Combining these assumptions with the timing noise levels estimated above we arrive at the estimate $(\Delta\Omega/\Omega)_{\text{glitch}} \gtrsim (0.02 - 0.2)I_B/I_{NS}$.

In Figure 3 we show the relative glitch sizes $(\Delta\Omega/\Omega)$ as a function of magnetic field for the glitching pulsars listed in the literature [16, 34]. We also include glitches from AXPs 4U 0142+61 [24], 1E 2259.1+586 [24], 1E 1841-045 [22], RXS J170849.0-400910 [22] and 1E 1048.1-5937 [26]. Also plotted is the ratio of the magnetospheric moment of inertia to the NS moment of inertia (I_B/I_{NS}) as a function of B_o , as well as 10%, and 1% of this value. We find that for $B_o \gtrsim 10^{13} \text{ G}$, the

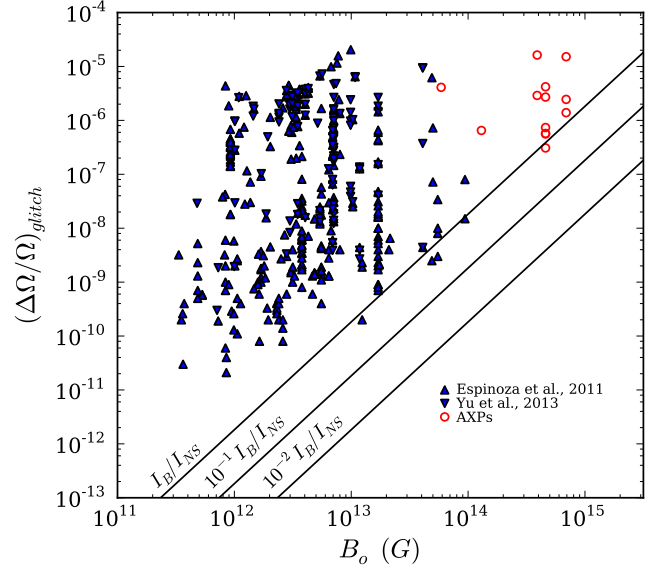


FIG. 3. Relative glitch size, $\Delta\Omega/\Omega$, versus the spin-down inferred magnetic field strength B_o , for radio pulsar glitches, taken from Espinoza *et al.* [34] and Yu *et al.* [16], and for AXP glitches [22, 24, 26]. The ratio of the magnetospheric moment of inertia to the total moment of inertia (I_B/I_{NS}), is also plotted as a function of B_o , along with 10% and 1% of I_B/I_{NS} . The minimum observed glitch size serves as a proxy for the timing noise, scaling with $(\Delta\Omega/\Omega)_{\text{min}} \sim 0.3 I_B/I_{NS}$ for $B_o \gtrsim 10^{13} \text{ G}$ and is consistent with our estimates of timing noise.

minimum observed glitch is roughly given by $(\Delta\Omega/\Omega)_{\text{glitch}} \gtrsim 0.3 I_B/I_{NS}$, which is consistent with our estimates above. Thus, we find consistent evidence from glitches for an increase with B_o of the timing noise floor.

While in principle a glitch due to change in the magnetospheric moment of inertia could be detected, it would require a large ($\gtrsim 10\%$) change in the total magnetospheric moment of inertia to be above the minimum detectable glitch size threshold set by the timing noise. Such an event would almost certainly be accompanied by torque variations and particle outflows, as seen during giant flares in SGRs, which would dominate the timing change due to the magnetospheric moment of inertia.

Discussion.— We have examined pulsar and AXP timing noise measurements reported in the literature and shown that a component of timing noise exists which depends on the spin-inferred dipole surface magnetic field strength ($S_{\text{FN}}/\Omega^2 \sim B_o^4$ such that $\sigma_{\text{TN}} \sim B_o^2 \Omega T^{3/2}$). This timing noise component begins to dominate at $B_o \sim 10^{12.5} \text{ G}$, and is responsible for a sharp rise in the floor of the timing noise values across both pulsar and AXP populations.

This provides yet another connection between high-B radio pulsars and AXPs, demonstrating a continuum of behaviors in these neutron stars, as independently suggested by, for example, quiescent X-ray luminosities of these objects [35], further ‘unifying’ radio pulsars and AXPs [36].

Variations near the open field lines can lead to mode chang-

ing and torque variability [5], however this would result in a frequency noise strength that scales as $S_{\text{FN}}/\Omega^2 \sim B_o^4\Omega^3$, and cannot explain the observed timing noise dependence.

We have shown that the magnetospheric moment of inertia is $I_B \sim 10^{-6} B_{15}^2 I_{\text{NS}}$, and have proposed a model of magnetospheric moment of inertia variation that fits the observations for both the observed timing noise strengths and the size of the smallest observable glitches in high magnetic field systems. This variation must occur near the neutron star surface, where the moment of inertia contribution is largest, as we find that timing noise due to variability confined near the light cylinder is too small to contribute significantly. Internal field evolution could also act as a source of moment of inertia variability.

This timing noise dependence provides evidence of rapid variability throughout the magnetosphere through moment of inertia variations. By assuming a rate similar to the known variability in the open field line regions of some pulsars [5, 6] we can estimate an amplitude for the variability of the magnetospheric moment of inertia $\Delta I_{\text{rms}} \sim (10^{-4} - 10^6) I_B$.

Recent observations [7] have also provided evidence that there exists rapid global variability in pulsar magnetospheres. We suggest that rapid global magnetospheric variability, perhaps due to reconnection or variable currents which are known to exist from pulsar simulations [33], acts as a source of timing noise through moment of inertia variations.

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